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THE TRANSIENT EXCITATION AND OSCILLATION TESTING
TECHNIQUE APPLIED TO A CAPTIVE MODEL

by

James A. Fein
James A. Kallio

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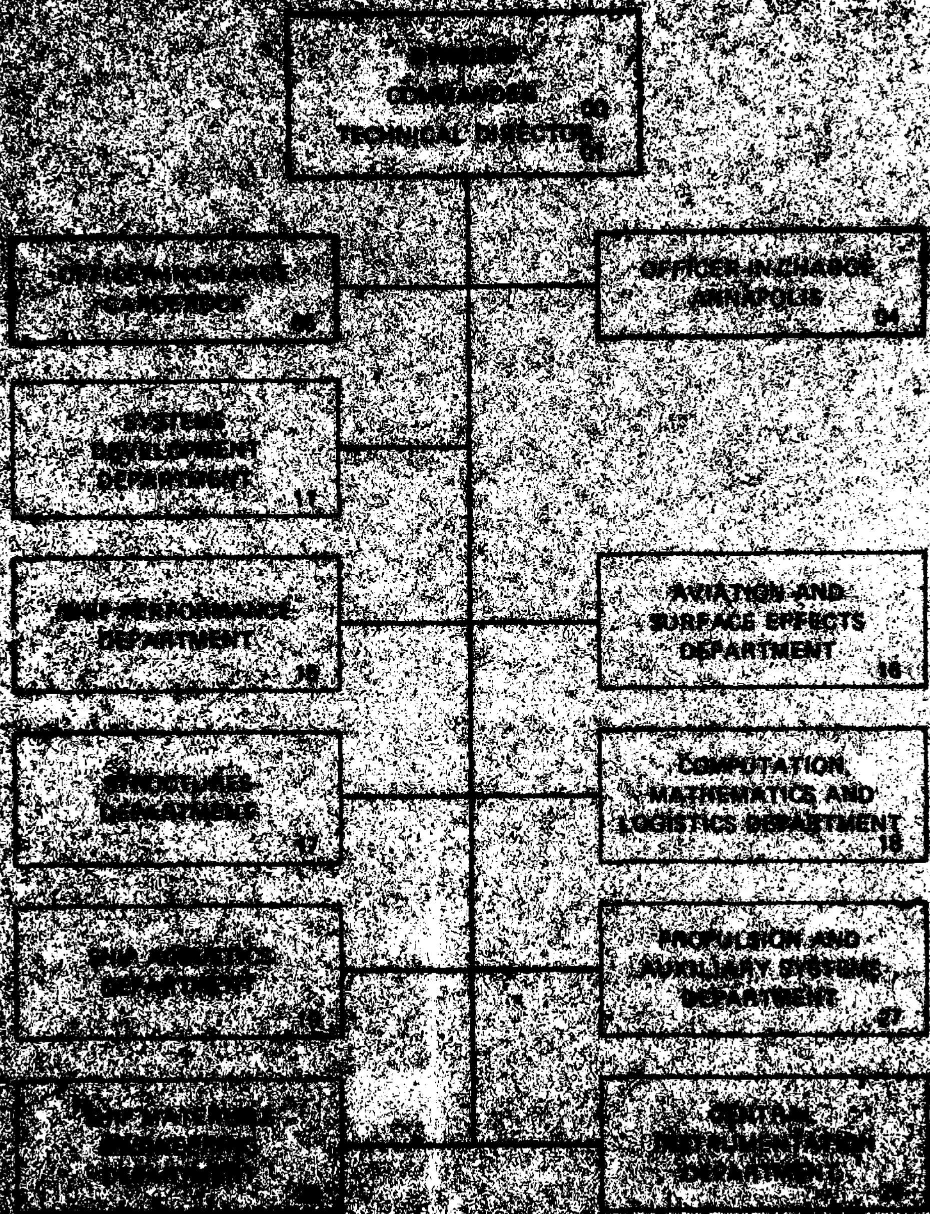
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Wave excitation and oscillation experiments were conducted to test a "transient" technique applied to a planing hull form model in the displacement mode. The "transient" technique uses a pulse which contains a range of frequencies (frequency packet). The technique is thus capable of gathering information that normally requires a series of single-frequency experiments. The heave exciting force and pitch moment obtained by the transient

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excitation technique are compared with those found by regular wave excitation. The coefficients from pitch and heave oscillations are also presented for both the transient technique and the regular (single-frequency) technique. The transient technique shows good correlation with the standard technique, yet obtains the experimental data of numerous single-frequency oscillations or wave excitations with a single data segment. This should lead to either a savings in data-gathering time or an increase in the information obtained over a given experimental period.

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SYMBOLS

A_{33}	Coefficient of vertical force due to heave acceleration
A_{35}	Coefficient of vertical force due to pitch acceleration
A_{53}	Coefficient of pitch moment due to heave acceleration
B_{55}	Coefficient of pitch moment due to pitch acceleration
B_{33}	Coefficient of vertical force due to heave rate
B_{35}	Coefficient of vertical force due to pitch rate
B_{53}	Coefficient of pitch moment due to heave rate
B_{55}	Coefficient of pitch moment due to pitch rate
C_{33}	Coefficient of vertical force due to heave displacement
C_{35}	Coefficient of vertical force due to pitch displacement
C_{53}	Coefficient of pitch moment due to heave displacement
C_{55}	Coefficient of pitch moment due to pitch displacement
g	Gravitational constant
h	Heave (vertical displacement, positive up)
h_w	Wave height
h_o	Heave oscillation amplitude (half amplitude)
$\dot{h}$	Time rate of change of heave
$\ddot{h}$	Acceleration in heave direction
$\bar{H}$	Nondimensional heave exciting force
I_{yy}	Pitch moment of inertia
K_{yy}	Radius of gyration in pitch
L	Characteristic length
m	Mass of model as seen by the force gages
M	Pitch moment (positive bow down)
$\bar{M}$	Nondimensional pitch exciting moment

M_{in}	In-phase component of pitch moment
M_{out}	Out-of-phase component of pitch moment
$\hat{M}$	Measured pitch moment amplitude
r_{θ}	Pitch radius of gyration
t	Time
Z	Vertical force (positive up)
Z_{in}	In-phase vertical force
Z_{out}	Out-of-phase vertical force
$\hat{Z}$	Measured vertical force amplitude
α	Angle of attack
δ	Pitch exciting moment phase
ε	Heave exciting force phase
ϕ_1	Oscillation force phase angle
ϕ_2	Oscillation moment phase angle
ω	Frequency
ω_e	Encounter frequency
$\bar{\mu}_e$	Nondimensional encounter frequency
θ	Pitch angle displacement (positive bow down)
θ_o	Pitch oscillation half amplitude
$\dot{\theta}$	Pitch rate (time rate of change)
$\ddot{\theta}$	Pitch acceleration
ΣM	Sum of moments in pitch direction
ΣZ	Sum of forces in vertical direction

ABBREVIATIONS

AGEH	Experimental hydrofoil ship designation. The first, and only, full-scale AGEH--called AGEH-1 and named the "PLAINVIEW"--was used as a test platform for the U.S. Navy's hydrofoil program. It is no longer in service.
CG	Center of gravity
deg	Degree
GM	Metacentric height
KG	Distance from keel to center of gravity
kg	Kilogram
m	Meter
N	Newton
s	Second

ABSTRACT

Wave excitation and oscillation experiments were conducted to test a "transient" technique applied to a planing hull form model in the displacement mode. The "transient" technique uses a pulse which contains a range of frequencies (frequency packet). The technique is thus capable of gathering information that normally requires a series of single-frequency experiments. The heave exciting force and pitch moment obtained by the transient excitation technique are compared with those found by regular wave excitation. The coefficients from pitch and heave oscillations are also presented for both the transient technique and the regular (single-frequency) technique. The transient technique shows good correlation with the standard technique, yet obtains the experimental data of numerous single-frequency oscillations or wave excitations with a single data segment. This should lead to either a savings in data-gathering time or an increase in the information obtained over a given experimental period.

ADMINISTRATIVE INFORMATION

This investigation was authorized and funded by the Naval Sea Systems Command (SEA 03) under the General Hydromechanics Research Program, SR-023-0101, Work Unit 1572-010.

INTRODUCTION

The objective of the present experiment was to demonstrate the transient oscillation technique and to obtain further verification for the transient wave excitation technique utilizing a model of the AGEH hydrofoil, without foils, in displacement mode. The hull was a planing hull but was operated well below planing speeds. The motivation for the work was to minimize the (often expensive) time spent on model experiments but not to sacrifice the quality of the data obtained.

The transient technique in general consists of the use of a frequency packet containing the range of pertinent frequencies to excite a model, thus extracting data for many frequencies from a single data run. The transient oscillation technique was first addressed in Reference 1*, where it is referred to as "force pulse testing." The pitch and heave oscillation coefficients were obtained for a surface ship model and compared to results of the standard technique. The transient technique was successfully applied to wave excitation experiments. This work[2] consisted

*A complete listing of references is given on page 31.

of measuring the force excited by a wave packet as it encountered a surface effect ship. Data was analyzed by Fourier methods and compared to the results of single-frequency wave excitation runs. Reference 3 gives a thorough derivation of the theory behind the technique and applies the transient approach to free model motions experiments. The references demonstrate that the technique has been in existence for over 15 years, though its utilization has been hampered by the lack of efficient data analysis routines which are now available.

In the current experiment, a model of a hullborne hydrofoil (without foils) was chosen so that results applicable to displacement ships could be obtained. Since AGEH hullborne motions were the subject of previous analytical work,[4] the possibility of correlation between theory and experiment existed.

This report contains a description of the model, a discussion of the experimental technique--emphasizing possible sources of error--a treatment of the data analysis procedures, a presentation of the results, and pertinent recommendations and conclusions. The results show that the transient technique for both wave excitation and oscillation work is a promising means of increasing experimental efficiency.

HYDROFOIL MODEL

A 1/12-scale model of the AGEH hydrofoil was employed in this experiment. This model was chosen because it represented a simple form that had been the subject of recent motion analysis. The model was utilized in the hullborne mode only, without foils or struts attached. The holes for the struts were closed and faired into the hull. The model was not powered during these experiments. Though the hull design is of the planing type, the speeds of the experiment were well below planing speeds.

The model is pictured in Figure 1 in the as-tested configuration. It had a displacement of 175 kg and a length of 5.24 m. The CG was located 2.34 m aft of the forward perpendicular on the waterline. The model longitudinal GM was measured to be 0.22 m, the pitch radius of gyration was 1.34 m, and the KG was 0.34 m. The model was tested at design CG and draft, which led to a very shallow draft on the aft one-third of the craft length. As can be seen in Figure 1 the model was very asymmetrical fore and aft, and this asymmetry had a very strong influence on the test results.

The full-scale AGEH has been a test platform for the U.S. Navy's hydrofoil program. It is no longer in service.

TEST TECHNIQUE

The experiment was conducted on Towing Carriage II of the Deep Water Basin at David W. Taylor Naval Ship Research and Development Center (DTNSRDC). The model was attached to the single-strut pitch-heave oscillator which was affixed to the surface towing beam of the carriage. This oscillator is a single-tow-point, scotch-yoke-driven, mechanically actuated device with a wide range of repeatable frequencies and amplitudes. The waves for the wave excitation experiments were generated by the Carriage II pneumatic wave maker which utilizes a variable air pressure to produce waves.

Two model attachment configurations were employed in the experiment. For the pitch oscillation the model was attached to the oscillator strut at the bow and to a fixed point located at the longitudinal and vertical CG. This configuration is shown in Figure 1 and in detail in Figure 2a. Pitch pivots at both attachment points allowed for forced pitching motion of the model. Block gages oriented to measure longitudinal and vertical force were located at each attachment point. The heave oscillations and wave excitation force experiments employed a towing arrangement where the oscillator strut was attached to a beam which was connected to two struts, as shown in Figure 2b. Thus the oscillator imparted pure heaving motion to the model. The pitch pivot connections, which could sustain no pitching moment, enabled the precise location of the reaction forces, thus enabling the computation of pitching moment from the measured reaction forces. It should be noted that the pivots were in line with the block gages at the vertical CG of the model so no corrections to the pitch moment due to off-line measurements were required.

Measurements taken during the oscillation experiments included the forces at the pivot points, the oscillator amplitude and frequency, and the carriage speed. During the wave excitation experiments, wave height was measured ahead of the model by a sonic probe. The measurements were recorded on analog magnetic tape and processed into digital form on the carriage.

The objectives of the test program were to establish the validity of the transient technique and to obtain information for frequency ranges of interest for the hullborne hydrofoil. Three speeds, corresponding to 1, 3, and 5 knots, full scale, were fully investigated; some work was conducted at zero speed. The single-frequency oscillation in heave and pitch covered a period range from 0.7 to 3.5 s, which

corresponds to full-scale periods from 2.5 to 12.5 s. The single-frequency waves for the wave excitation experiments were chosen with periods from 1.5 to 3.5 s, which correspond to full-scale wave periods of 5 to 12.5 s. These periods cover the typical modal periods of sea states up to Sea State 5. Within the frequency range specified for each speed, up to eighteen single-frequency runs were executed. Amplitude was varied to check linearity; all data was obtained within the linear range. (Oscillation double amplitudes varied from 0.8 to 2 cm.)

The single-frequency oscillation and wave excitation experiments were conducted in the standard manner: the model was first brought to speed, then the oscillation was initiated, steady conditions were achieved, and ten cycles of data were taken. The transient wave experiments were conducted by bringing the carriage to speed as the approaching wave packet was being generated, then the trip down the tank was timed to encounter the full composite wave while at speed. Achieving the full spectrum of frequencies requires careful timing and also coordination between wave maker, carriage operator, and test personnel. The transient wave is generated by the wave maker in response to a prerecorded magnetic tape segment. A sample transient wave from the experiment is given in Figure 3. An explanation of the method for specifying the transient wave is given in Reference 3. For the transient oscillations the frequency of the oscillator was varied manually, with the frequency sweep covering the full frequency range of interest. Runs were conducted with varying sweep rates, starting at either the maximum or minimum frequency. A sample oscillation amplitude trace is shown in Figure 4. The oscillator motion itself was esentially error free, but any looseness in the pivots or deflection of the model could lead to possible error.

ANALYSIS OF DATA

The data was obtained in a body-axis coordinate system but transformed into the earth-fixed (inertial) system so that the data could be used in seakeeping analysis. The coordinate transformation does not introduce error into the analysis procedures. Since oscillation and wave excitation analysis assumes linearity, forces not associated with the first harmonic were neglected. These forces were, however, monitored and found to be quite small. The coordinate system and terminology were chosen in accordance with seakeeping practice:[4]

θ = pitch (positive bow down)

h = heave (positive up)

h_w = wave height (positive up)

OSCILLATIONS

The form of the coefficients and the derivation of the equations follow the method of Reference 5.

The total force and total moment for pitch and heave oscillations are given by

$$\Sigma Z = (A_{33}+m)\ddot{h} + B_{33}\dot{h} + C_{33}h + A_{35}\ddot{\theta} + B_{35}\dot{\theta} + C_{35}\theta \quad (1)$$

and

$$\Sigma M = (A_{55}+I_{yy})\ddot{\theta} + B_{55}\dot{\theta} + C_{55}\theta + A_{53}\ddot{h} + B_{53}\dot{h} + C_{53}h \quad (2)$$

During oscillations, vertical force components are measured at the bow and CG, the sum of which gives the total Z force. The bow component multiplied by the longitudinal moment arm to the CG (aft pivot) gives the pitch moment.

In the data analysis process, for each discrete frequency ω the motion is considered to be sinusoidal. The force and moment each have a phase angle with respect to the motion, denoted by ϕ_1 and ϕ_2, respectively:

$$\begin{aligned}\Sigma Z &= \hat{Z}\sin(\omega t-\phi_1)\\ &= \hat{Z}\cos\phi_1 \sin\omega t - \hat{Z}\sin\phi_1 \cos\omega t\end{aligned} \quad (3)$$

and

$$\begin{aligned}\Sigma M &= \hat{M}\sin(\omega t-\phi_2)\\ &= \hat{M}\cos\phi_2 \sin\omega t - \hat{M}\sin\phi_2 \cos\omega t\end{aligned} \quad (4)$$

where $\hat{Z}$ and $\hat{M}$ are amplitudes of Z force and M moment, respectively.

The amplitudes of the in-phase and out-of-phase components are defined as

$$Z_{in} = - \hat{Z} \cos\phi_1, \; Z_{out} = - \hat{Z} \sin\phi_1$$

and (5)

$$M_{in} = - \hat{M} \cos\phi_2, \; M_{out} = - \hat{M} \sin\phi_2$$

The pitch and heave motion are defined as

$$\theta = \theta_o \sin\omega t$$

$$\dot{\theta} = \omega\theta_o \cos\omega t \qquad (6)$$

$$\ddot{\theta} = - \omega^2 \theta_o \sin\omega t$$

and

$$h = h_o \sin\omega t$$

$$\dot{h} = \omega h_o \cos\omega t \qquad (7)$$

$$\ddot{h} = - \omega^2 h_o \sin\omega t$$

Setting Equations (3) and (4) equal to Equations (1) and (2), and utilizing the definitions of pitch and heave contained in Equations (6) and (7), enables the evaluation of the coefficients in terms of the measured quantities. When separated into sin ωt and cos ωt components, and given in terms of the measured quantities, the nondimensional coefficients are

$$\overline{A}_{35} = - (Z_{in}/\theta_o - C_{35}) \frac{1}{m\omega^2 L} \qquad (8)$$

$$\overline{B}_{35} = - (Z_{out}/\theta_o) \frac{1}{m\omega\sqrt{gL}} \qquad (9)$$

$$\bar{A}_{55} = - \quad (M_{in}/\theta_o - C_{55}) \frac{1}{m\omega^2 L^2} + r_\theta^2/L^2 \qquad (10)$$

$$\bar{B}_{55} = - (M_{out}/\theta_o) \frac{1}{m\omega L \sqrt{gL}} \qquad (11)$$

$$\bar{A}_{33} = - (Z_{in}/h_o - C_{33}) \frac{1}{m\omega^2} - 1.0 \qquad (12)$$

$$\bar{B}_{33} = - (Z_{out}/h_o) \frac{L}{m\omega\sqrt{gL}} \qquad (13)$$

$$\bar{A}_{53} = - (M_{in}/h_o - C_{53}) \frac{1}{m\omega^2 L} \qquad (14)$$

$$\bar{B}_{53} = - (M_{out}/h_o) \frac{1}{m\omega\sqrt{gL}} \qquad (15)$$

The data analysis procedures solve Equations (8)--(15) to provide the coefficient results from the oscillation data. In addition, air oscillations were conducted to obtain the mass and moment or inertia for inclusion in the calculations. The static coefficients C_{35}, C_{55}, C_{33}, and C_{53} were obtained from static tests at constant variations of trim angle and heave height. Speed effects on these terms were negligible, except for C_{55} at the highest speed where the speed effect was about 10 percent. No speed effects were included in the data analysis.

The transient oscillations were also analyzed using Equations (8)--(15). Prior to the calculation of coefficients the measurements of force and moment were expressed as functions of frequency (frequency response functions) using the Fourier analysis program for irregular wave data. The frequency domain data was then resolved into small finite-frequency steps, and the frequency-dependent coefficients were computed for each frequency step. The results depend heavily on the selection of frequency increment since too small an increment leads to an overresolved result with too many extraneous peaks. On the other hand, too large a frequency increment

can obscure valid peaks. No general policy can be stated for selection of step size until there is more experience with this test technique.

WAVE EXCITATION

The wave excitation analysis for both regular and transient waves is described in detail in Reference 2. The transient data is processed to obtain frequency domain information as was done for the oscillation results. The phase of the force results was referenced to the wave height phase angle as transferred to the CG. The model was held captive at level trim in all wave conditions. The measured heave exciting force $\hat{Z}$ was the sum of the vertical force components. The nondimensional heave force is defined as

$$\overline{H} = \frac{L\hat{Z}}{h_w mg} \tag{16}$$

The measured pitch moment was obtained from the bow vertical force component multiplied by the moment arm. The nondimensional moment is defined as

$$\overline{M}_z = \frac{\hat{M}}{h_w mg} \tag{17}$$

The phase associated with heave force is ε, while the phase associated with pitch moment is δ. The nondimensional frequency μ_e is given by

$$\mu_e = \omega_e \sqrt{L/g} \tag{18}$$

RESULTS

The results of the experiments are contained in Figures 5--18. Figures 5 and 6 present the static zero speed results that establish the corrective tare terms (C_{33}, C_{35}, C_{53}, and C_{55}) used in calculating the nondimensional oscillation coefficients. Figures 7--14 contain comparisons of the two experimental techniques for obtaining the coefficients. Figures 15--18 contain comparisons of the wave excitation results, obtained by two experimental techniques, for heave force, pitch moment, and the associated phases at four different model speeds (including zero speed).

STATICS

The statics data was obtained at zero speed and is essentially a function of the ship geometry reflected in the buoyancy distribution. Figure 5a gives the variation of vertical force with pitch angle. The force is linear for only a small range. At negative pitch angles (bow up) the heave force does not increase but tends to drop to zero because the ship has a relatively wide bow area with high deadrise and a very fine stern. The stern does not pick up much force as pitch angle becomes more negative. This lack of symmetry and high deadrise bow could have caused errors in the results if the model flexed, and thus buoyancy changed, especially in the coupling terms. The moment due to pitch angle (Figure 5b) is better behaved, with a linear range of ± 1 deg. It is noted that during the pitch oscillation experiments, the amplitude of oscillation remained within the linear range of ± 0.5 deg. The vertical force variation with heave displacement (Figure 6a), which is a direct function of the variation of waterplane area, is quite linear (within the range of the heave oscillation amplitudes). The pitch moment variation with heave (Figure 6b), on the other hand, is nonlinear and shows some scatter. This term is small, however, and should not contribute much error to the coefficient calculation. The dimensional static terms used in the calculation of coefficients are

$$\begin{aligned} C_{33} &= -\ 22{,}800 \text{ Nt/m} \\ C_{35} &= -\ 7{,}980 \text{ Nt/rad} \\ C_{53} &= -\ 1{,}250 \text{ Nt-m/m} \\ C_{55} &= -\ 42{,}750 \text{ Nt-m/rad} \end{aligned} \tag{19}$$

As mentioned previously, the speed effects on the static terms were small for this model so they did not enter into the analysis process.

OSCILLATIONS

The oscillation data is presented in Figures 7 to 14. The results of the pitch oscillation are given first, followed by the heave results. Each figure contains data points from the regular oscillation runs and a solid line denoting the results of the transient oscillation. The transient oscillation technique provided continuous information over a frequency range, so separate points were not practical.

The added moment of inertia term $\bar{A}_{55}$ is presented in Figure 7 for model speeds of 1, 3, and 5 knots. The transient results agree reasonably well for all speeds but do not predict the large low-frequency value at 1 knot. Scatter in the regular pitch results tends to cloud the data trends. This scatter could be due to interactions between the model and reflected waves at the low speed. The moment damping derivative $\bar{B}_{55}$ is shown in Figure 8. The agreement is very good at 1 and 3 knots; at 5 knots the transient is lower in magnitude than the regular results by a constant amount throughout the frequency range, although the difference is not large.

Figure 9 contains the relatively small coupling derivative $\bar{A}_{35}$. The transient values for the $\bar{A}_{35}$ term are consistently more negative than the regular oscillation results. Results agree better at the high- and low-frequency ends than in the mid-frequency range. This term may have inherent error because it is calculated by taking a difference of large numbers, namely the measured quantity and the tare term C_{35}. The determination of C_{35} itself is error prone, as noted in the discussion of Figure 5a. Much better agreement is found for the coupling term $\bar{B}_{35}$ in Figure 10. This derivative, calculated directly without tare corrections, shows excellent agreement at all speeds.

The heave oscillation results are given in Figures 11--14. Heave added mass $\bar{A}_{33}$ is shown in Figure 11. Figure 11a shows good agreement between the two techniques, though the regular oscillation is subject to some scatter. The other two speeds show excellent agreement for this important term. Heave damping $\bar{B}_{33}$, given in Figure 12, shows a similar situation. There is scatter at the low speed, but overall the agreement is good.

The coupling term $\bar{A}_{53}$ is shown in Figure 13. As with $\bar{A}_{35}$ the two techniques agree on trends but show some lack of agreement at the mid frequencies. This derivative is calculated by using the tare term C_{53} and, thus, is subject to nonlinearities and errors in that term, as seen in Figure 6b. Also it is important to note that this term is an order of magnitude smaller than $\bar{A}_{33}$. The coupling term $\bar{B}_{53}$ in Figure 14 shows good agreement between the techniques.

Overall, the agreement between the transient and regular oscillation techniques is good, except for those derivatives that depend on tare terms that are nonlinear and asymmetrical. Even for those terms, the trends are well represented and the magnitudes are close. The important terms are well duplicated by the transient technique at all speeds. The differences for $\bar{A}_{53}$ and $\bar{A}_{35}$ are more due to the model's

hydrostatics than to weaknesses in either oscillation technique. In any oscillation experiment on a surface model, the buoyancy tare terms must be carefully measured. Any flexing in the model or high deadrise angle at the waterline can lead to problems in the accuracy of the measurements.

WAVE EXCITATION

Figures 15--18 compare the nondimensional heave exciting forces $\overline{H}$, the heave phases ε, the nondimensional pitch exciting moments $\overline{M}$, and the moment phases δ at model speeds of 0, 1, 3, and 5 knots. As in Reference 2, the agreement between the data points for regular waves and the transient results is excellent. Both the trends and the magnitudes of the phases and forces from the regular wave technique are accurately duplicated by the transient wave results. The transient wave technique provides more information about frequency dependence of the terms and requires much less testing time than the regular wave technique. Some scatter is apparent in the regular wave results at the lower speeds.

CONCLUSIONS AND RECOMMENDATIONS

1. The transient technique is applicable for obtaining wave excitation forces and moments, and it saves time while providing more detailed information on frequency dependence. The technique can be applied to models of displacement ships for wave heights within the linear range.

2. The transient oscillation technique can be applied to vertical plane oscillations in pitch and heave. Results agree with the single-frequency technique, except where model geometry introduces uncertainties into the results of both techniques. The transient technique saves time during the experiment by replacing a series of single-frequency runs with a single transient run for each speed. A time savings of 90 percent would be possible if ten single-frequency points are replaced by one transient data point that covers the frequency range of interest.

3. The verification of the transient technique should be extended to the horizontal plane maneuvering coefficients and more work done to find the best approach for generating the transient oscillation pulse and for analyzing the results.

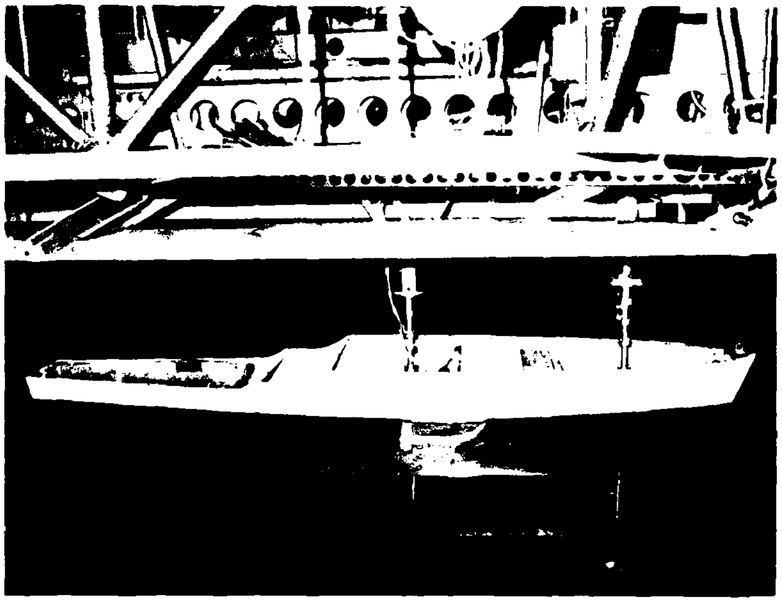
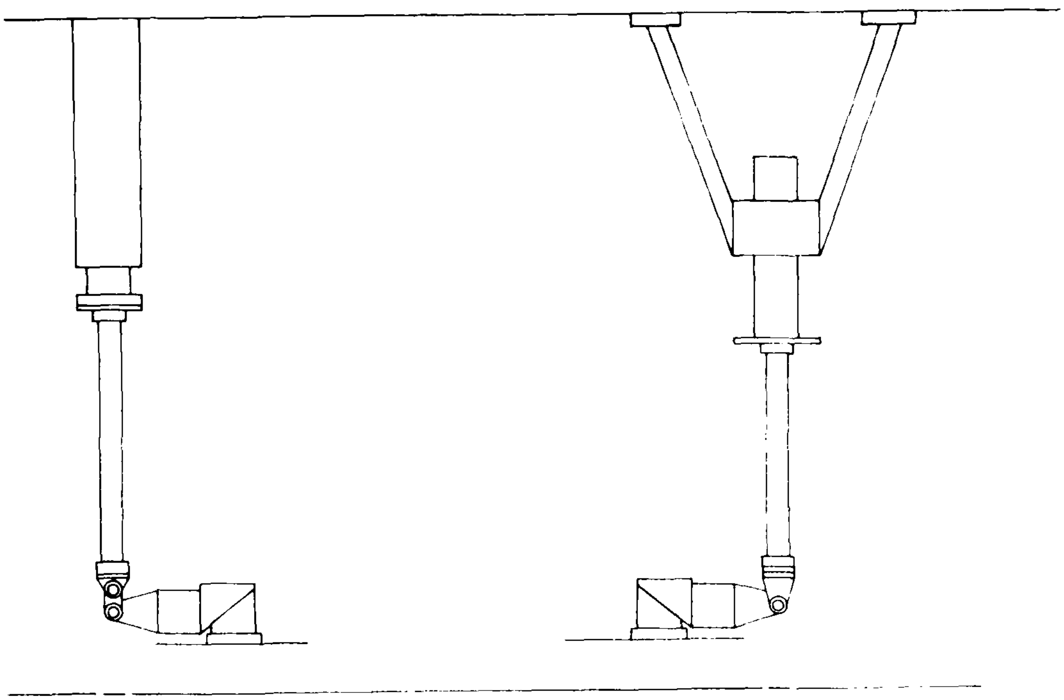


Figure 1 - Photograph of Hydrofoil Test Model 4916



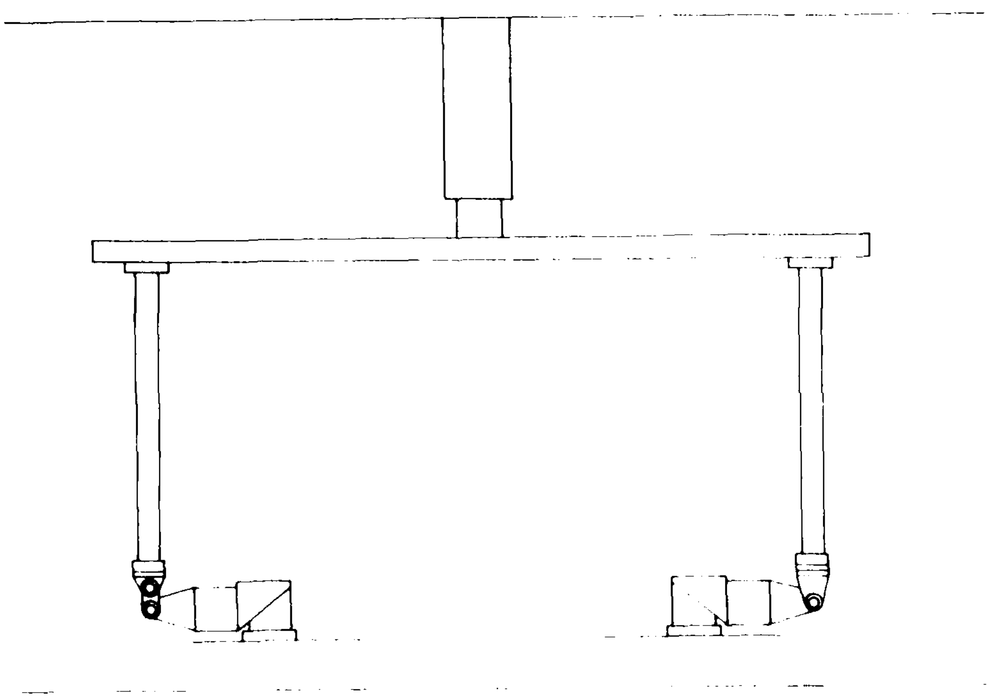


Figure 2 - Experimental Set Up for (a) Pitch Oscillations and (b) Heave Oscillations and Wave Excitation

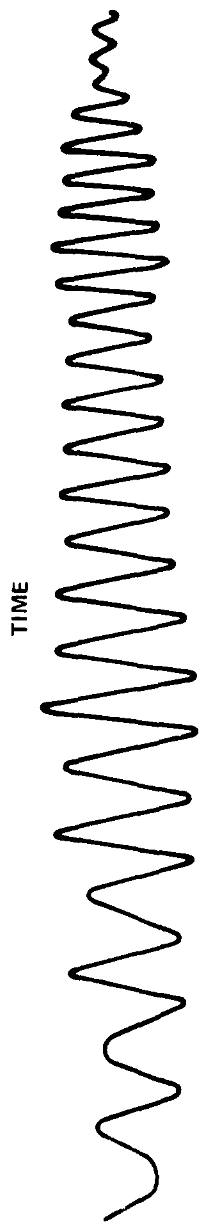


Figure 3 - Example of Transient Wave (Run 3007)

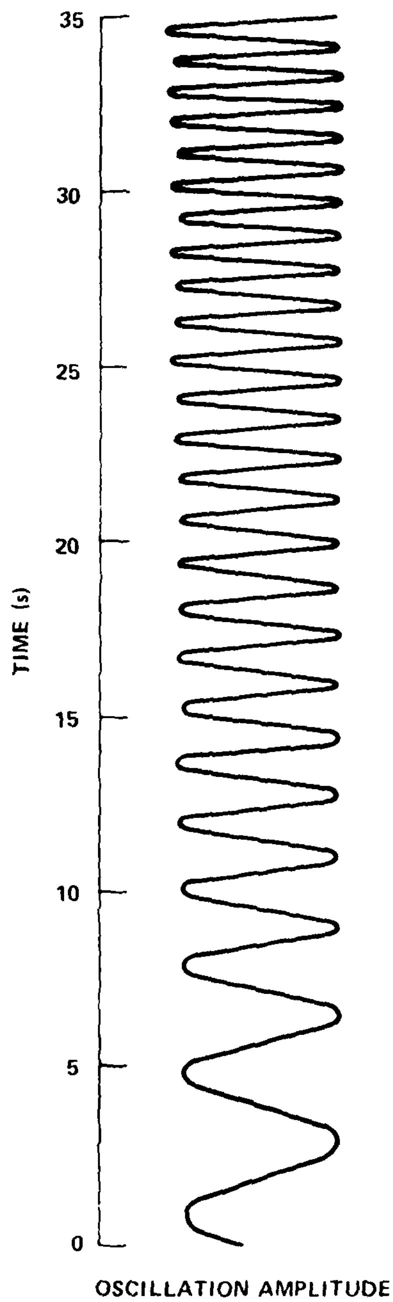


Figure 4 - Sample Oscillation Amplitude Trace (Run 1153)

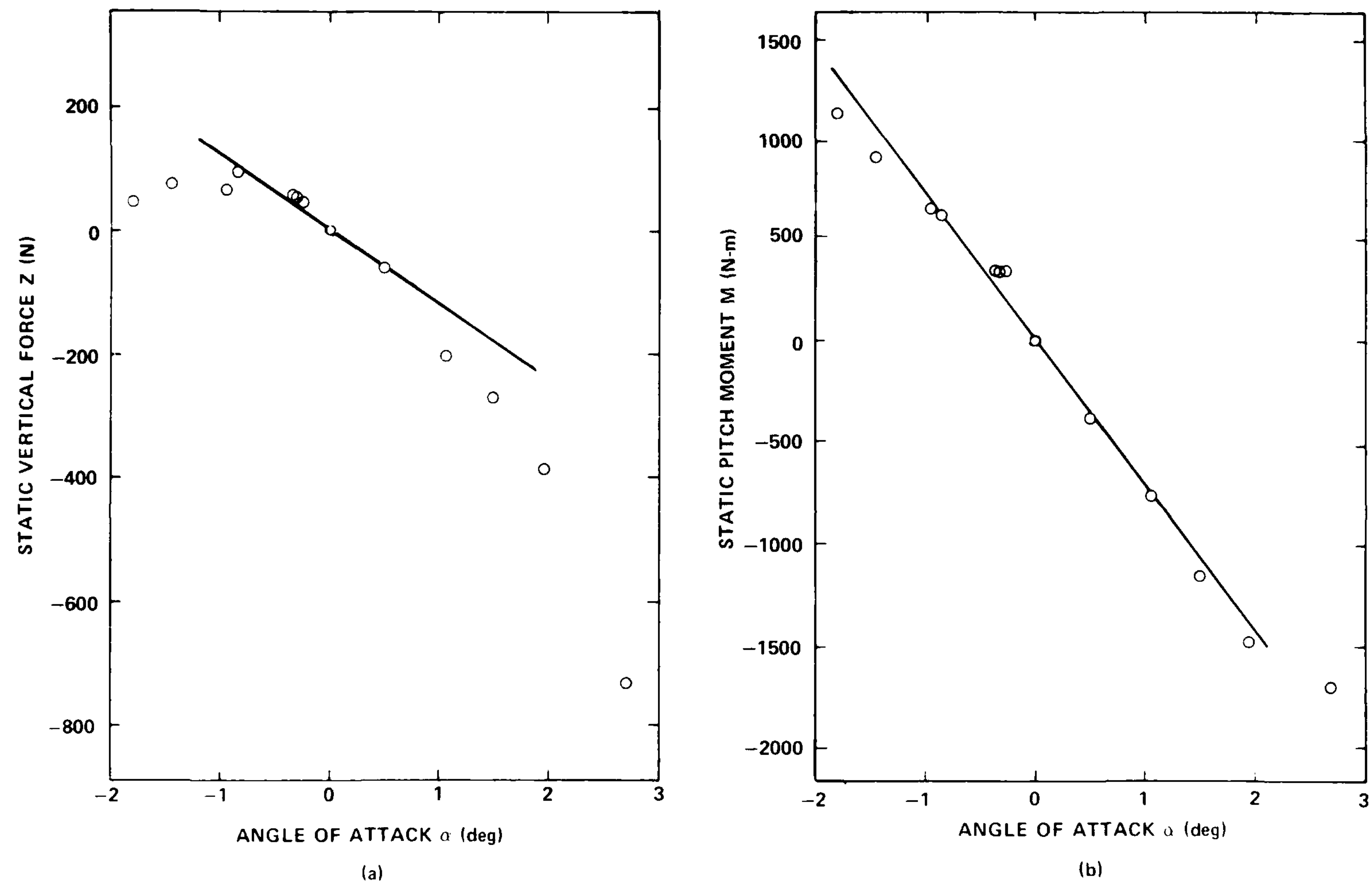
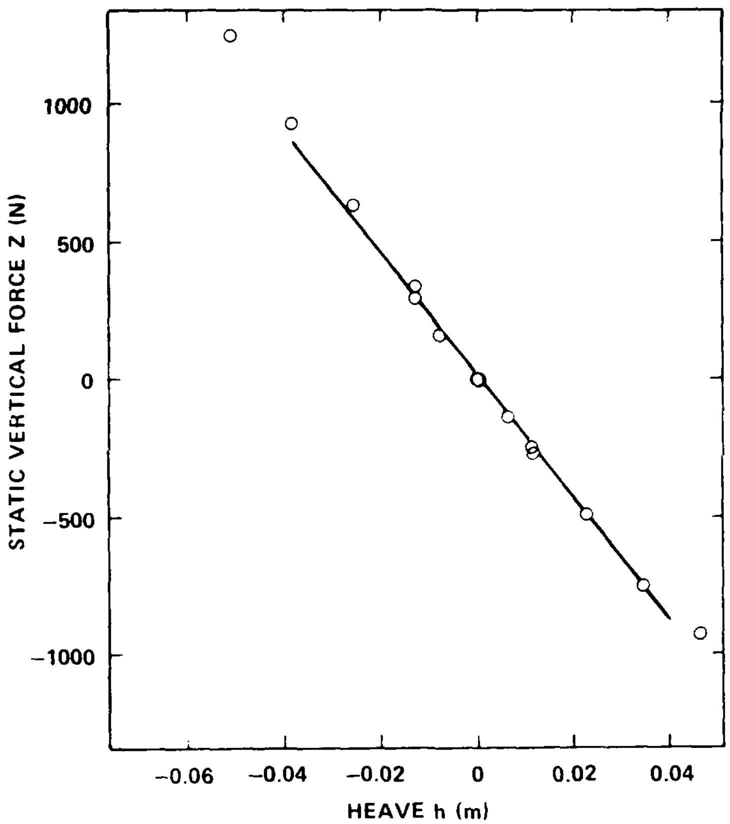
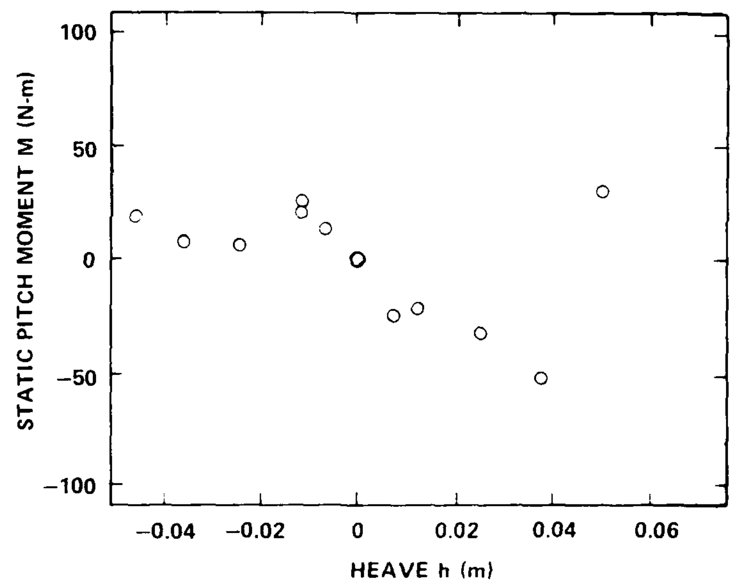


Figure 5 - Variation of (a) Static Vertical Force and (b) Static Pitch Moment with Pitch Angle for Model Speed of Zero



(a)



(b)

Figure 6 - Variation of (a) Static Vertical Force and (b) Static Pitch Moment with Heave for Model Speed of Zero

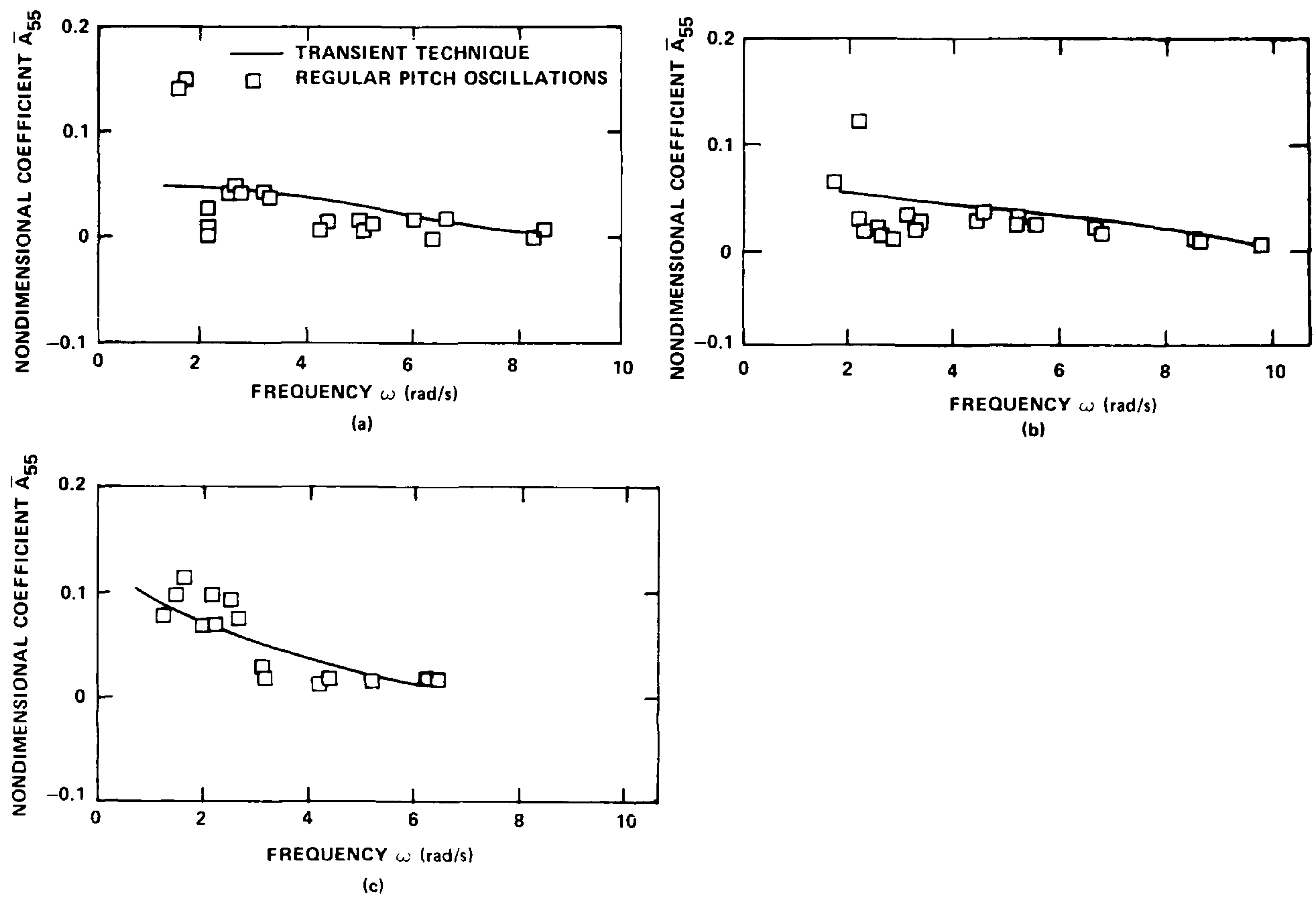


Figure 7 - Variation of Nondimensional Coefficient $\bar{A}_{55}$ with Frequency for Transient and Regular Oscillations at Model Speeds of (a) 1 Knot, (b) 3 Knots, and (c) 5 Knots

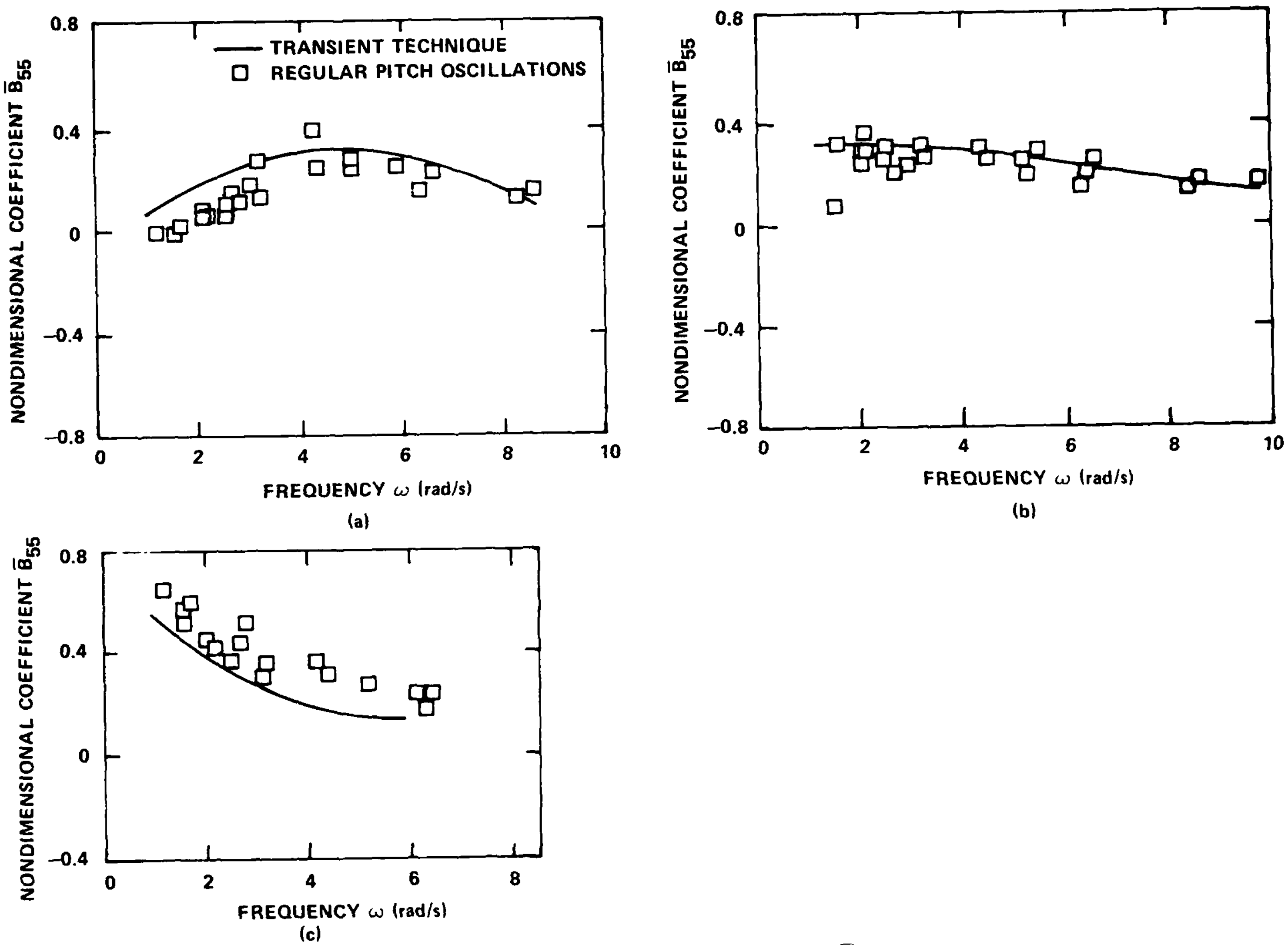


Figure 8 - Variation of Nondimensional Coefficient $\bar{B}_{55}$ with Frequency for Transient and Regular Oscillations at Model Speeds of (a) 1 Knot, (b) 3 Knots, and (c) 5 Knots

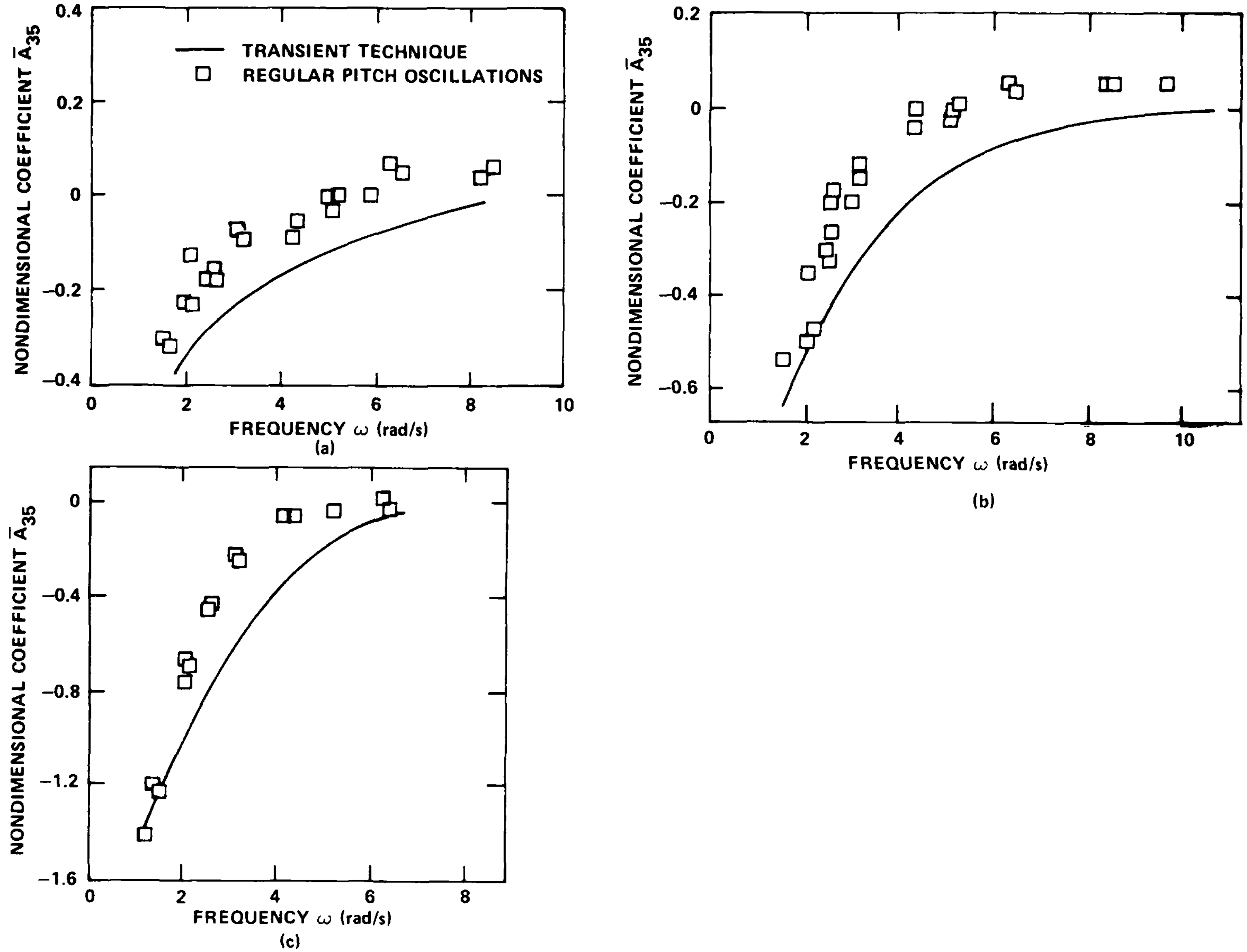


Figure 9 - Variation of Nondimensional Coefficient $\bar{A}_{35}$ with Frequency for Transient and Regular Oscillations at Model Speeds of (a) 1 Knot, (b) 3 Knots, and (c) 5 Knots

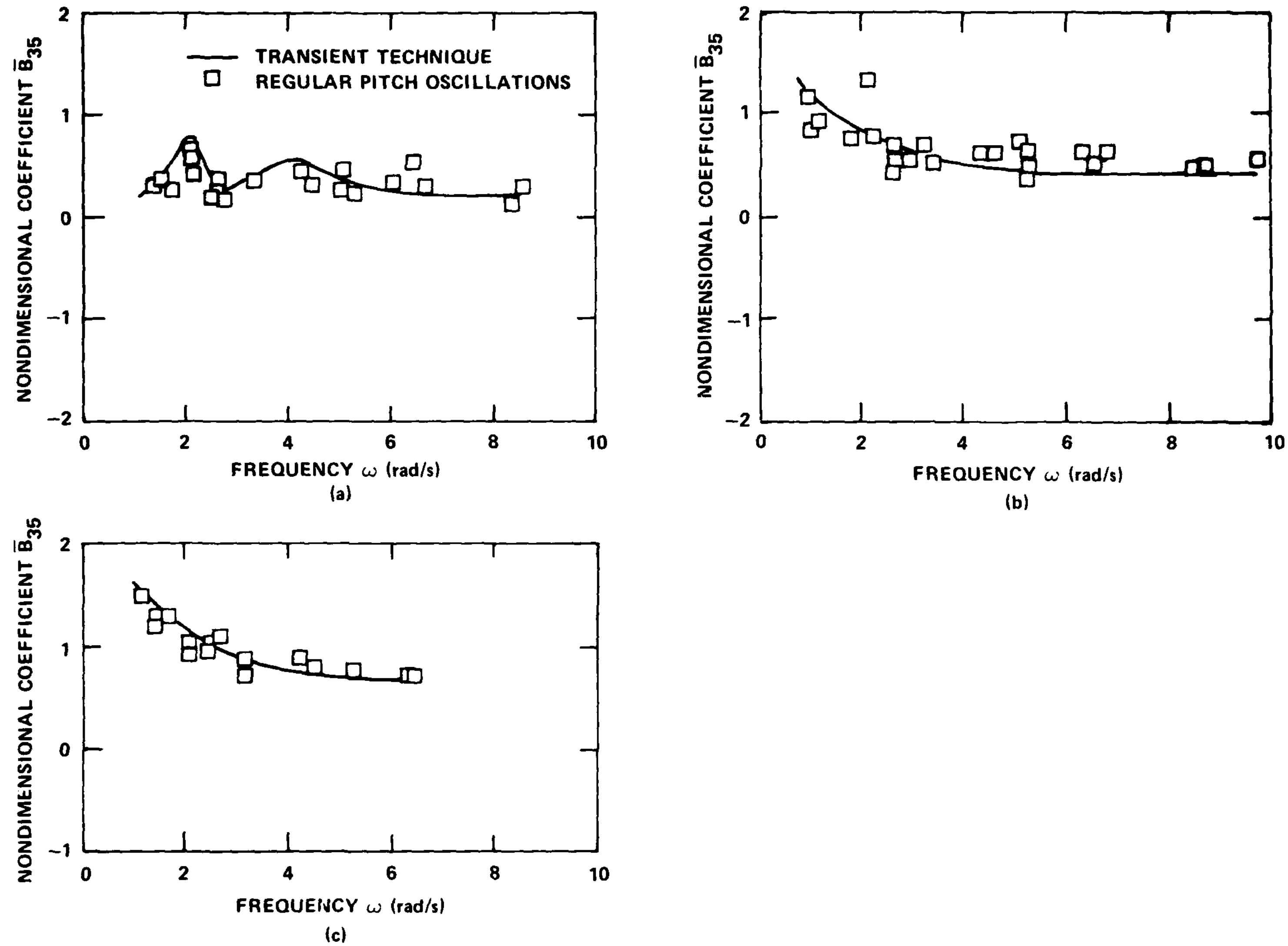


Figure 10 - Variation of Nondimensional Coefficient $\bar{B}_{35}$ with Frequency for Transient and Regular Oscillations at Model Speeds of (a) 1 Knot, (b) 3 Knots, and (c) 5 Knots

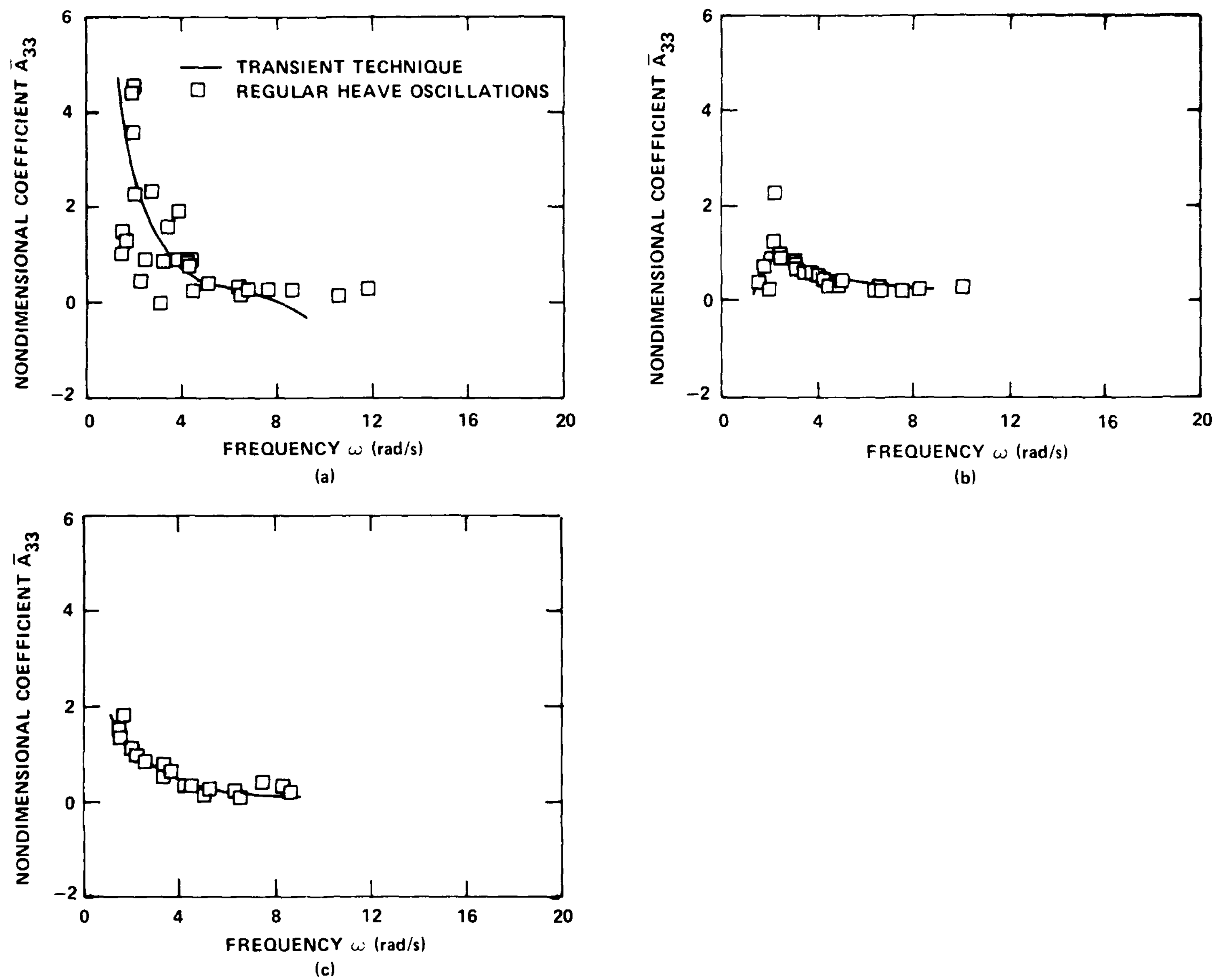


Figure 11 - Variation of Nondimensional Coefficient $\bar{A}_{33}$ with Frequency for Transient and Regular Oscillations at Model Speeds of (a) 1 Knot, (b) 3 Knots, and (c) 5 Knots

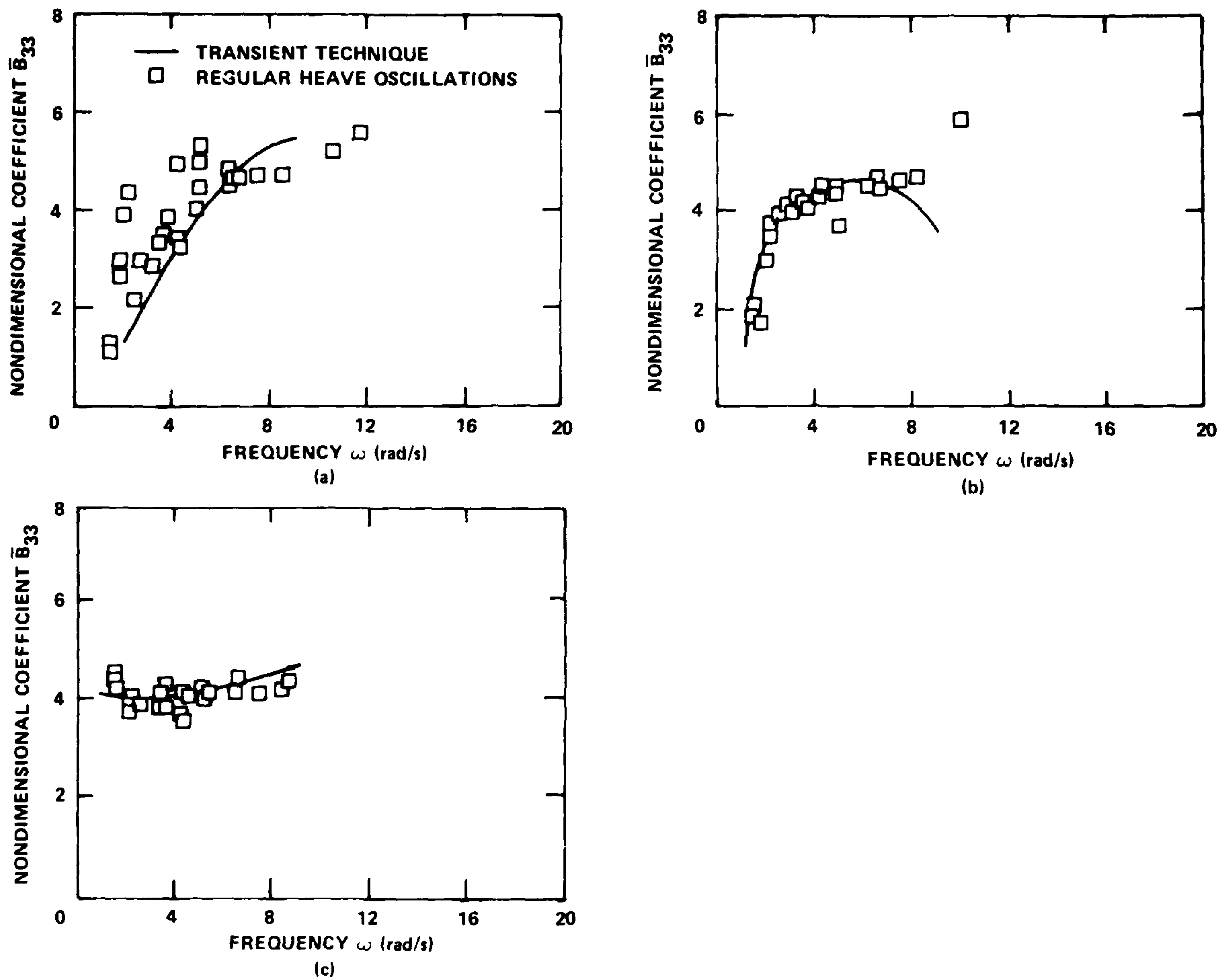


Figure 12 - Variation of Nondimensional Coefficient $\bar{B}_{33}$ with Frequency for Transient and Regular Oscillations at Model Speeds of (a) 1 Knot, (b) 3 Knots, and (c) 5 Knots

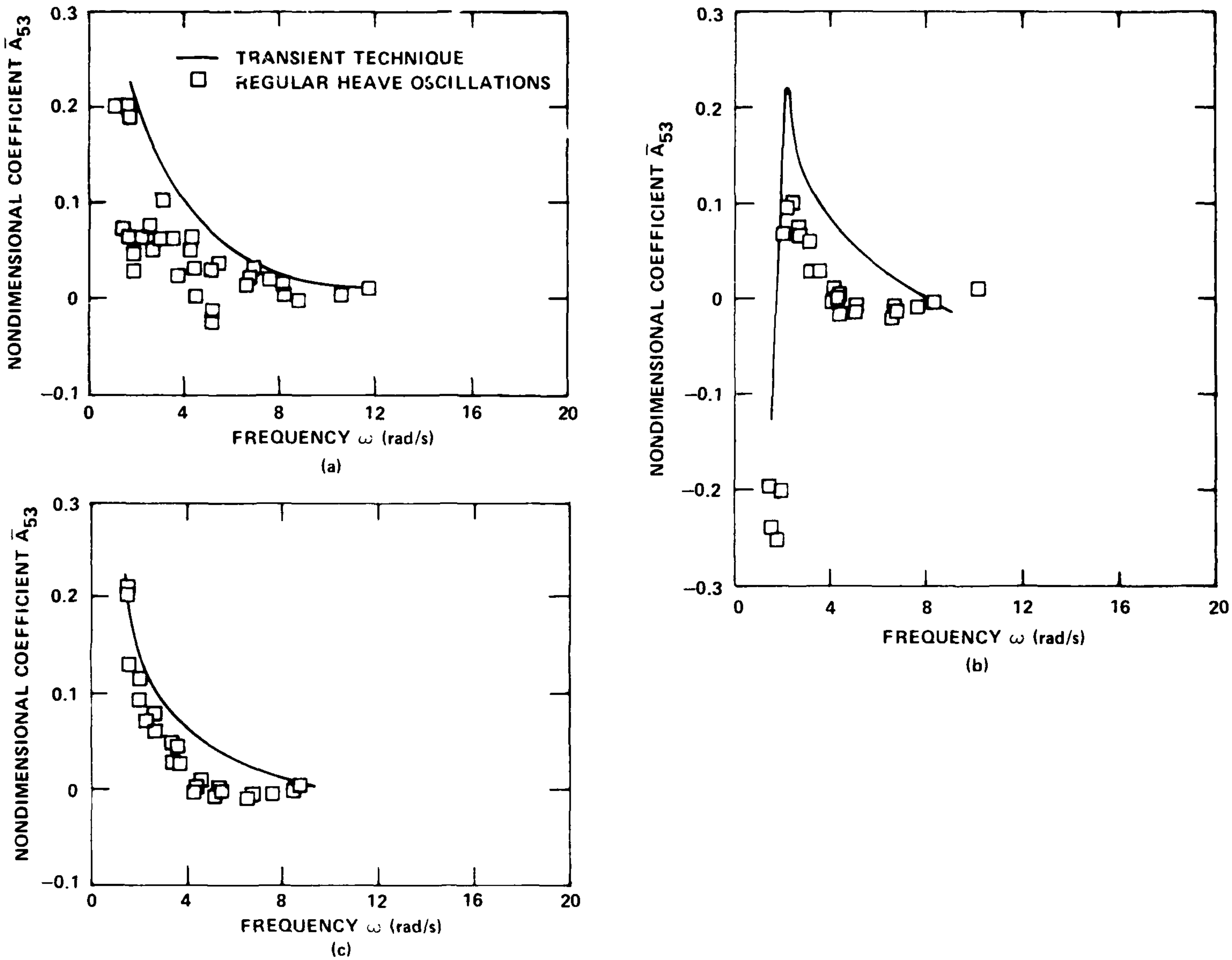


Figure 13 - Variation of Nondimensional Coefficient $\bar{A}_{53}$ with Frequency for Transient and Regular Oscillations at Model Speeds of (a) 1 Knot, (b) 3 Knots, and (c) 5 Knots

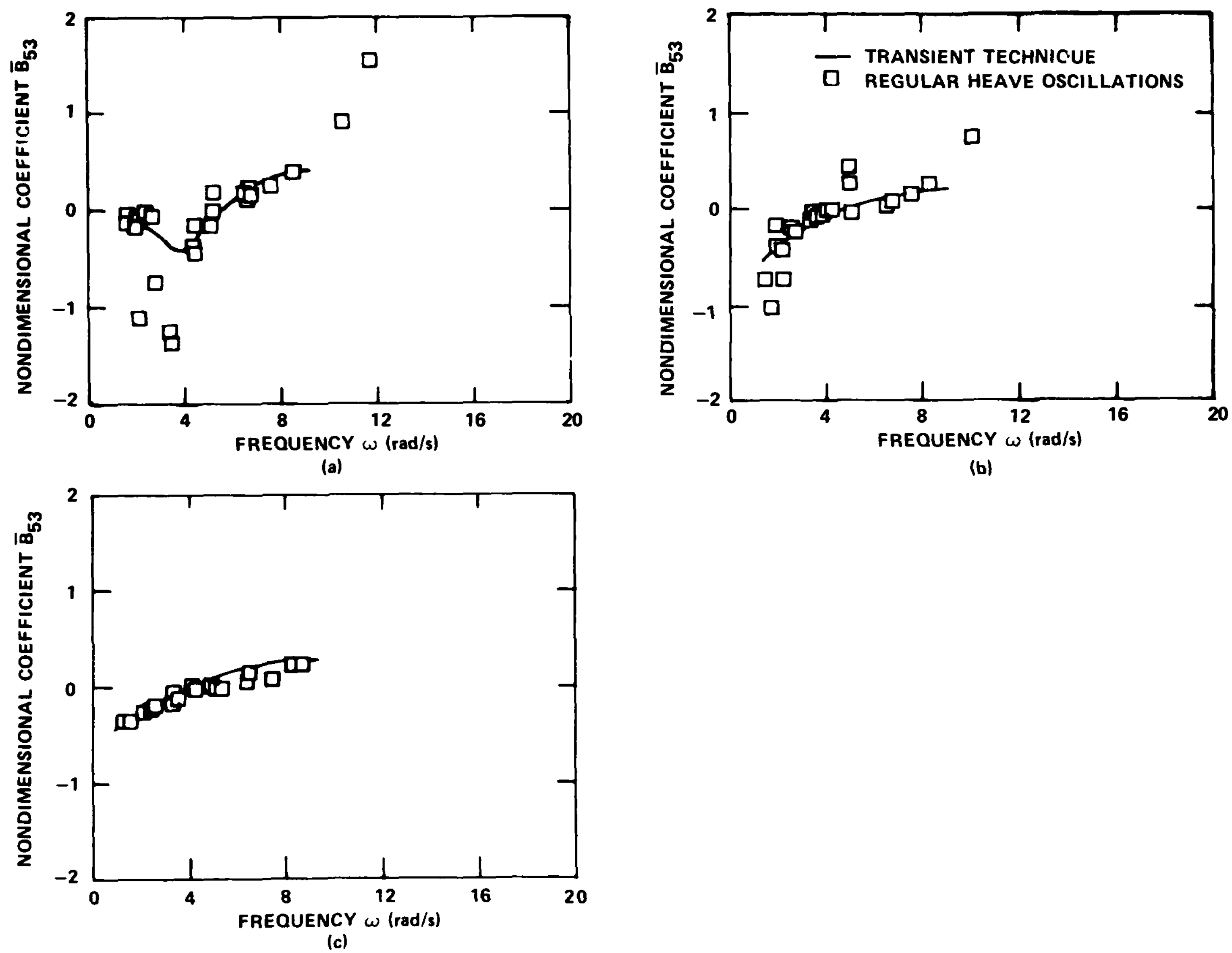


Figure 14 - Variation of Nondimensional Coefficient $\bar{B}_{53}$ with Frequency for Transient and Regular Oscillations at Model Speeds of (a) 1 Knot, (b) 3 Knots, and (c) 5 Knots

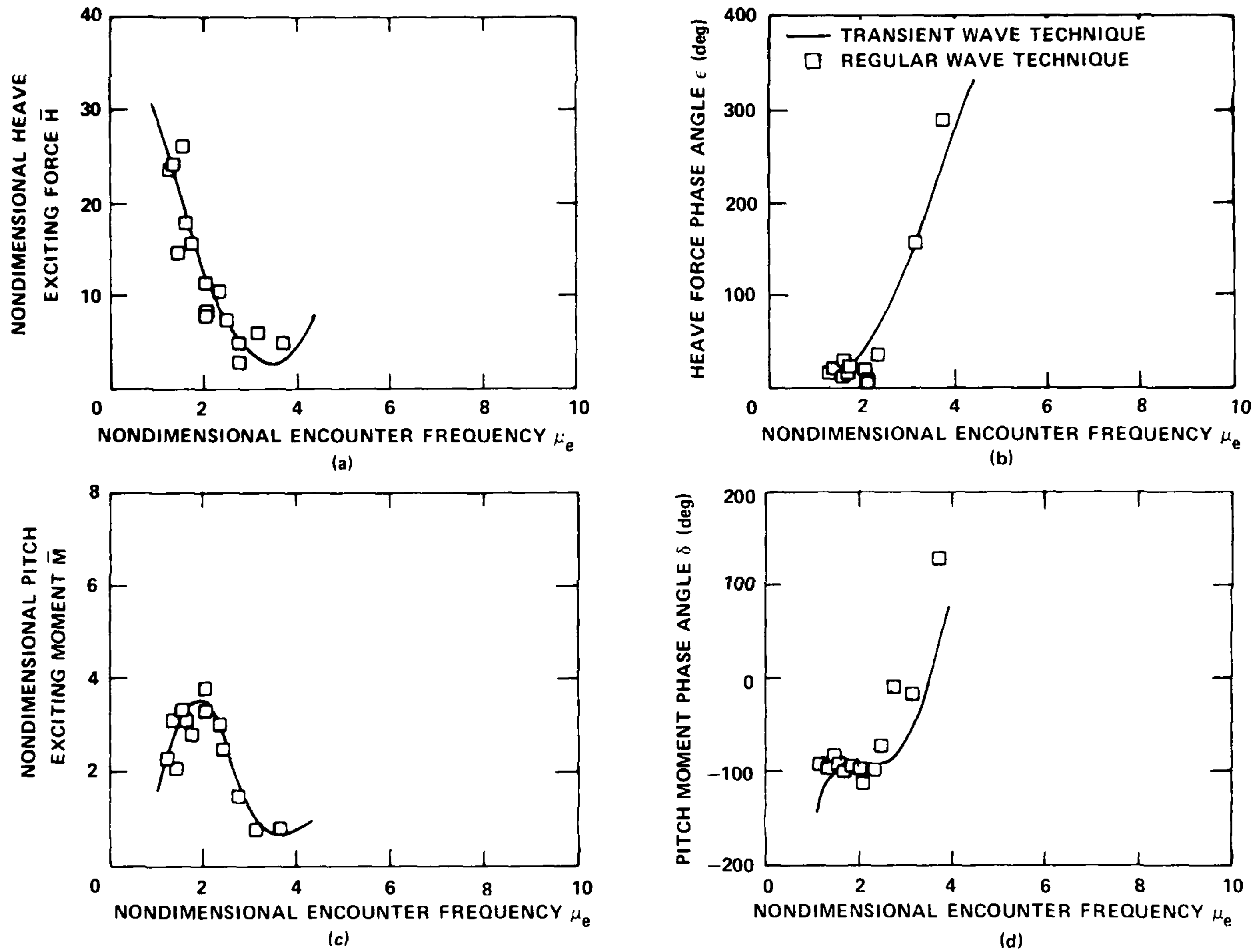


Figure 15 - Variation of (a) Nondimensional Heave Exciting Force, (b) Heave Exciting Force Phase Angle, (c) Nondimensional Pitch Exciting Moment, and (d) Pitch Moment Phase Angle with Nondimensional Encounter Frequency at Zero Speed by Two Experimental Techniques

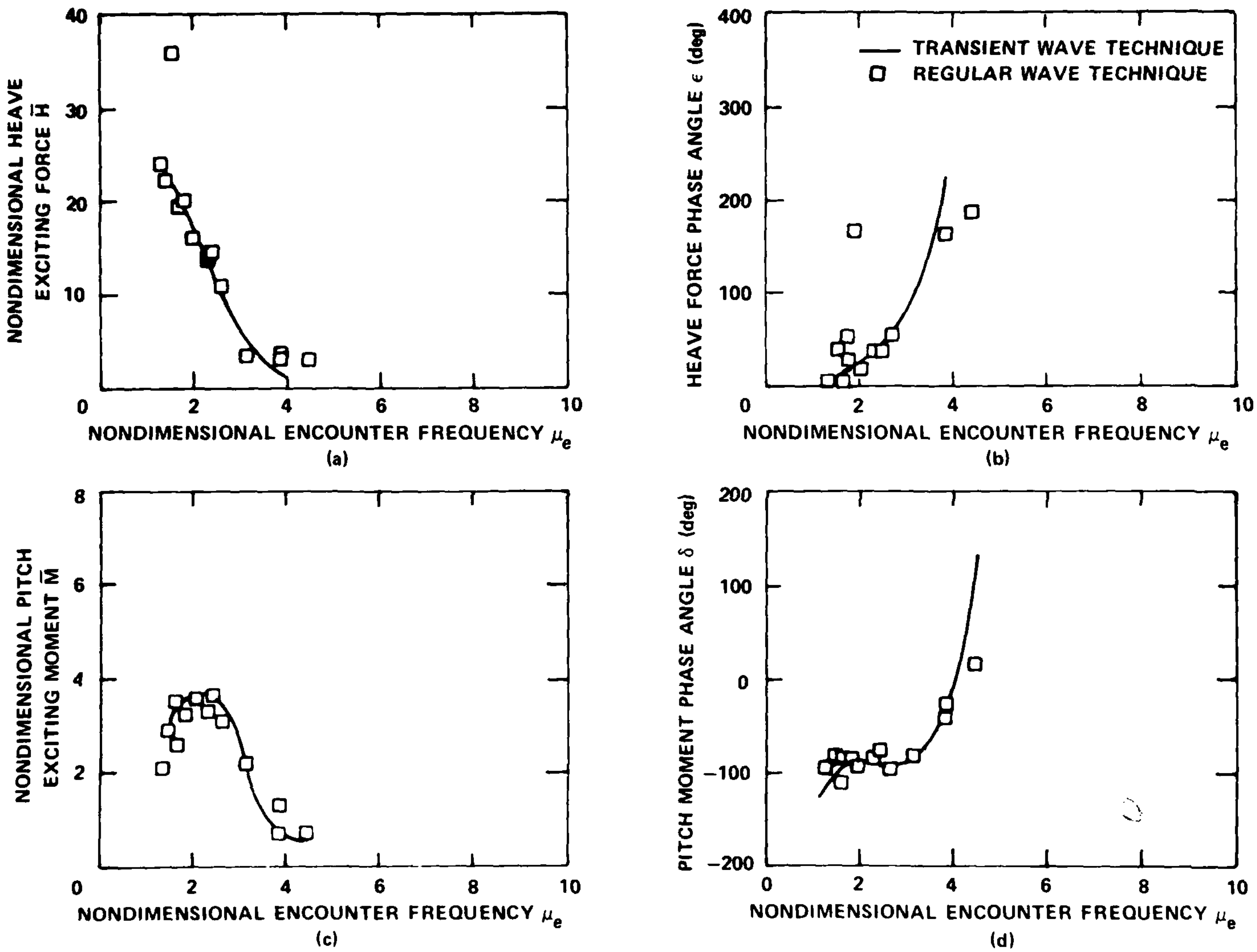


Figure 16 - Variation of (a) Nondimensional Heave Exciting Force, (b) Heave Exciting Force Phase Angle, (c) Nondimensional Pitch Exciting Moment, and (d) Pitch Moment Phase Angle with Nondimensional Encounter Frequency at a Speed of 1 Knot by Two Experimental Techniques

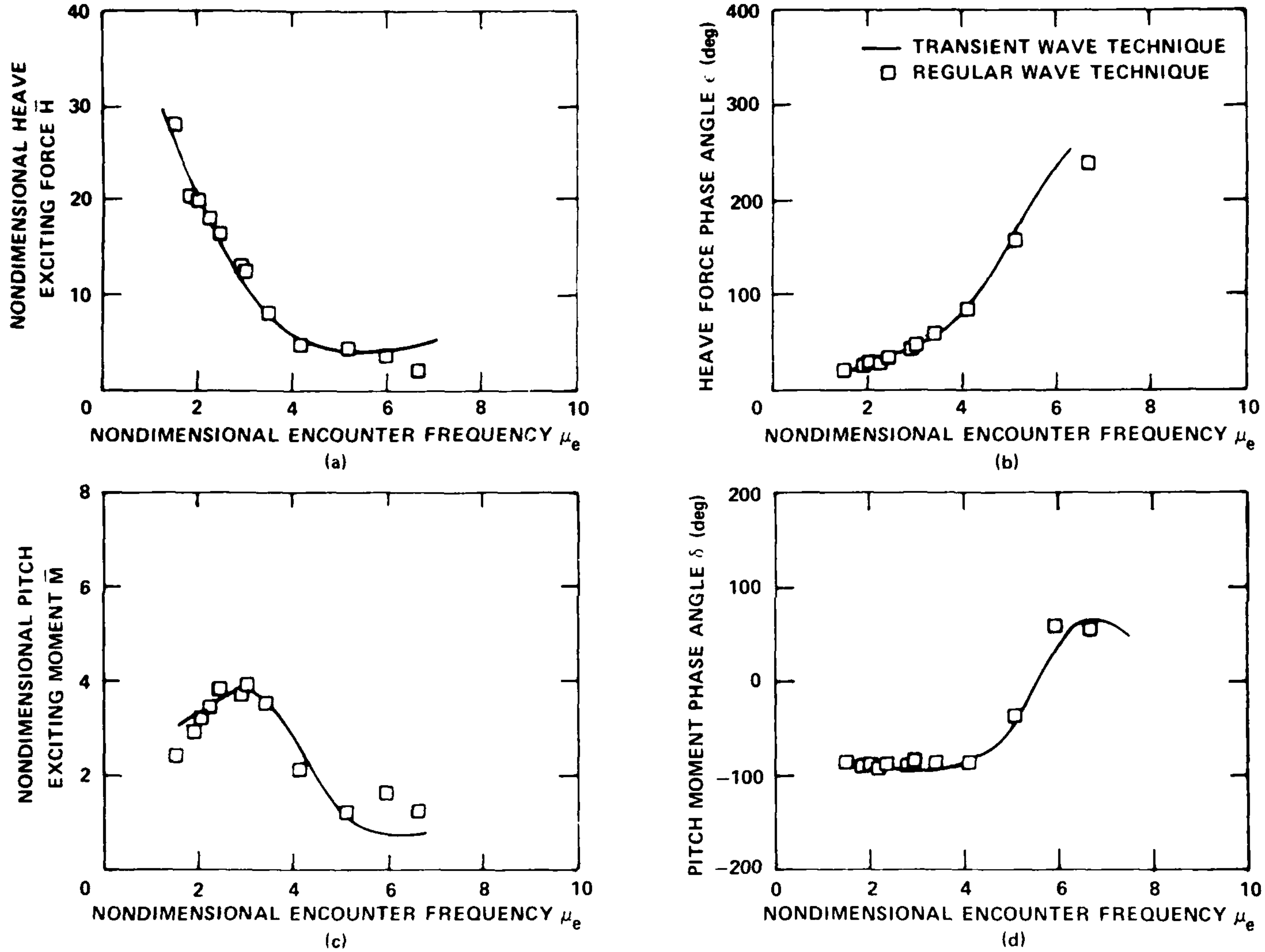


Figure 17 - Variation of (a) Nondimensional Heave Exciting Force, (b) Heave Exciting Force Phase Angle, (c) Nondimensional Pitch Exciting Moment, and (d) Pitch Moment Phase Angle with Nondimensional Encounter Frequency at a Speed of 3 Knots by Two Experimental Techniques

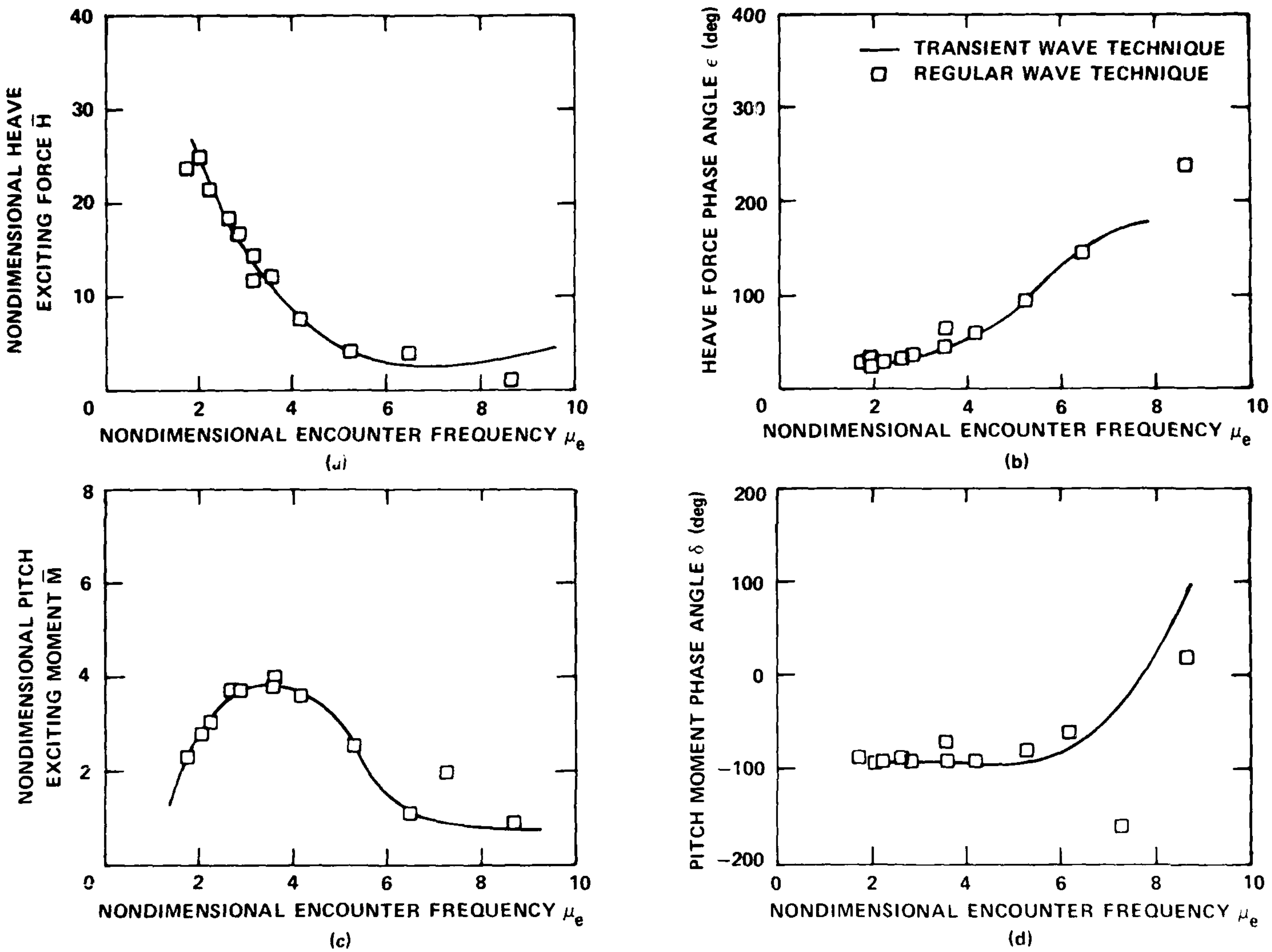


Figure 18 - Variation of (a) Nondimensional Heave Exciting Force, (b) Heave Exciting Force Phase Angle, (c) Nondimensional Pitch Exciting Moment, and (d) Pitch Moment Phase Angle with Nondimensional Encounter Frequency at a Speed of 5 Knots by Two Experimental Techniques

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